Research Article

Study on Compaction Effect and Process of Reclaimed Soil of Nonmetallic Mines in Xinjiang, China

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Reclaimed soil is the key substrate for land reclamation and ecological restoration in the mine areas. The change of the density of reclaimed soil of the nonmetallic mines in Xinjiang during the land reclamation process was studied in this paper. Firstly, the in situ test method of static load was used to simulate the compaction of reclaimed soil with different thickness of overlying soil by different compaction times of mines reclamation machinery, and field in situ test compaction data were obtained. Then, the numerical simulation method was used to simulate the variation process of displacement and porosity at different depths for different thickness of the reclaimed soil under different compaction conditions. The numerical simulation and the in situ test results verified each other to acquire the compaction process and results of reclaimed soil under different compaction. The results showed that the numerical simulation results were consistent with the in situ test. The reclaimed soil thickness and compaction times were crucial factors affecting the compaction effect of the soil. The difference between the three times compaction and the uncompacted soil was obvious, and the effect of single compaction was weakened with the increase of compaction times. Under the same compaction action, the thicker the soil was, the less obvious the compaction effect would be. In the process of reclamation, the compaction effect of the surface part (at the depth of 10 cm) was visible, and the amount of compression and springback was larger. The research results can provide a reference to the land reclamation of nonmetallic mines in Xinjiang, China.

1. Introduction

There are vast nonmetallic mineral resources in Xinjiang, and large-scale exploitation of mineral resources is bound to cause irreversible damages to the local ecological environment. The open-pit mining method is mainly adopted. Mines with open-pit mining form deep open pits and a large number of massive hard waste rocks, excavating and occupying numerous land resources (Figures 1 and 2). Mine enterprises must carry out land reclamation work after mine closure. In order to reclaim mines into grassland or woodland, covering soil is an reasonable measure to carry out for land reclamation work. In the process of this work, the reclamation machines will inevitably have a compaction effect on the surface soil, impacting on the quality of the reclaimed soil, thus holding back the ecological restoration of surface vegetation in the mining area. The surface soil of nonmetallic mines in Xinjiang is mostly sandy loam soil, and the soil texture is different from other places. Therefore, it is of great significance to grasp the compaction change of reclaimed soil in the process of land reclamation in Xinjiang.

Recently, studies on the soil compaction have yielded fruitful results, such as the effect of compaction on water infiltration in soil [1], the changes of physical and chemical properties of the reclaimed soil after compaction [2–9], the effect of using different reclamation materials on the soil compaction [10–12], the impact of compaction on the water content of soil [13–19], the effect of compaction on the soil structure [20, 21], and the effect of different compaction conditions on porosity of reclaimed soil [22]. According to

FIGURE 1: Open-pit mining area.

FIGURE 2: Waste rock piles.

the previous research results, it was found that studies on the compaction of soil were mostly concentrated on the agricultural field, and the compaction studies of the reclaimed soil in the mining area were mostly focusing on the soil reclamation in the coal mining area. In the past, the research on compaction simulation of reclaimed soil was mainly carried out through the field physical simulation test. The obtained soil compaction results could not reflect the change process of reclaimed soil under compaction. The reclaimed soil parameters obtained by physical simulation would also vary depending on the test method.

In view of the limitations of the past studies and the unique characteristics of the sandy soil of the nonmetallic mining zone, this study simulated the compaction effect of reclamation machinery on the reclaimed soil by the numerical simulation method. By comparing the numerical simulation results with the field physical simulation test results, the change process and law of reclaimed soil of nonmetallic mines in Xinjiang under different compaction were summarized, which provides a basis for land reclamation of nonmetallic mines in this region.

2. Physical Simulation Results of Reclaimed Soil Compaction Test

2.1. Experimental Materials. The reclaimed soil sample was taken from a limestone mining area in Dabancheng district, Urumqi, Xinjiang. The reclaimed soil was calcic brown soil and belonged to sandy loam. The bulk density of the reclaimed soil was $12.646 \, kN/m^3$ with 57.71% porosity and

11.76% water content. The lower part of the reclaimed soil was backfilled with waste rocks from this limestone mining area.

2.2. Experimental Design. The widely used reclamation machines in Xinjiang are track-type bulldozers. In order to study the changes in the physical properties of the soil under different compaction effects of reclamation soil with different thicknesses, six 2 meter deep test barrels were set up (Figure 3).In these barrels, limestone waste rock was laid in the lower part (Figure 4), and 30 cm, 50 cm, and 70 cm thick reclamation soil was laid in the upper layer. During the experiment, the flat load test method was used for 6 test barrels to simulate the instantaneous pressure of the NT855-B280 crawler bulldozer on the ground (Figure 5). The simulated pressure was 33.7 kPa, and the compaction times were 0, 1, 3, and 5 times (Figures 6 and 7). After compaction, in order to observe the changes in the physical properties of the soil, samples were taken at 10 cm, 30 cm, 50 cm, and 70 cm in 6 test barrels. Three samples were taken with ring knives at each depth. Finally, the collected soil samples were sent to laboratory for tests of natural density, moisture content, and porosity. The experimental process is detailed in the technical roadmap (Figure 8).

2.3. Experimental Data Compiling. A total of 16 groups of 48 soil samples were obtained in the compaction experiment. The topsoil with thickness of 50 cm and 70 cm was divided into 2 layers to collect samples. The topsoil with thickness of 30 cm at the depth of 30 cm could not be sampled as it was the interface between soil and waste rocks. Alternatively, samples at the depth of 10 cm were collected. The results of the compiled experimental data are shown in Table 1.

3. Numerical Simulation of Reclaimed Soil Compaction Test

3.1. Numerical Simulation Analysis Scheme. PFC2D is used to simulate the numerical simulation analysis. The thickness of the soil and the number of compaction were used as the dependent variables. The Mohr–Coulomb model was used as the yield criterion to analyze the effects of different reclamation methods (thickness of soil and compaction times) on porosity at different depths of reclaimed soil.

3.2. Computational Model. The particle size composition of the reclaimed soil calculation model is shown in Table 2. The soil sample of the compaction test was loose particles. The soil particle unit was defined as a rigid body, the model between the particles was defined as a linear elastic model, the model between the particle and the wall was defined as an elastic model, and the wall was defined as a confined rigid body. The model was the left and right and bottom boundary constraints, and the upper part was the free boundary of cyclic loading and unloading. The calculation model dimensions are shown in Tables 3 and 4. Because the reclaimed soil was compacted for a short time, gravity was not considered in the calculation process.
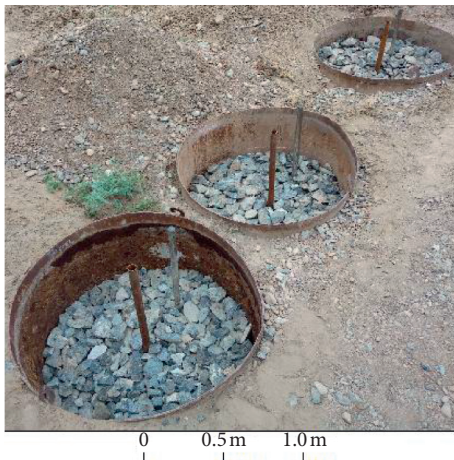
FIGURE 3: Empty cylindrical test barrels.

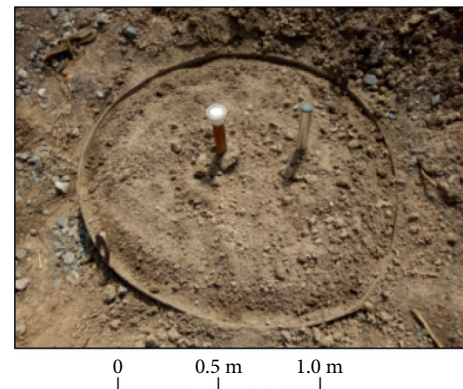FIGURE 4: Backfilled waste rock at lower part of test barrels.

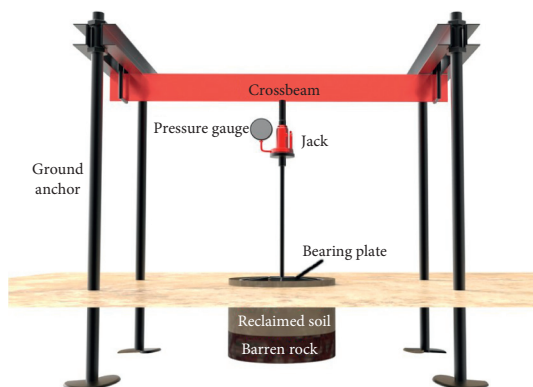FIGURE 6: Uncompacted reclaimed soil test barrel.

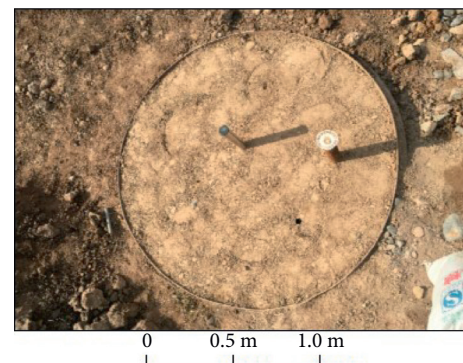FIGURE 5: Illustration of the setup for plate load test.

FIGURE 7: Reclaimed soil after one-compaction test barrel.

3.4. Numerical Simulation Results

3.4.1. Numerical Simulation Results of Covered 30 cm Soil Thickness under Compaction. The numerical simulation results of the soil thickness of 30 cm are shown in Figures 9–14 and summarized in Table 6. Table 6 shows that the soil particles have different degrees of subsidence after
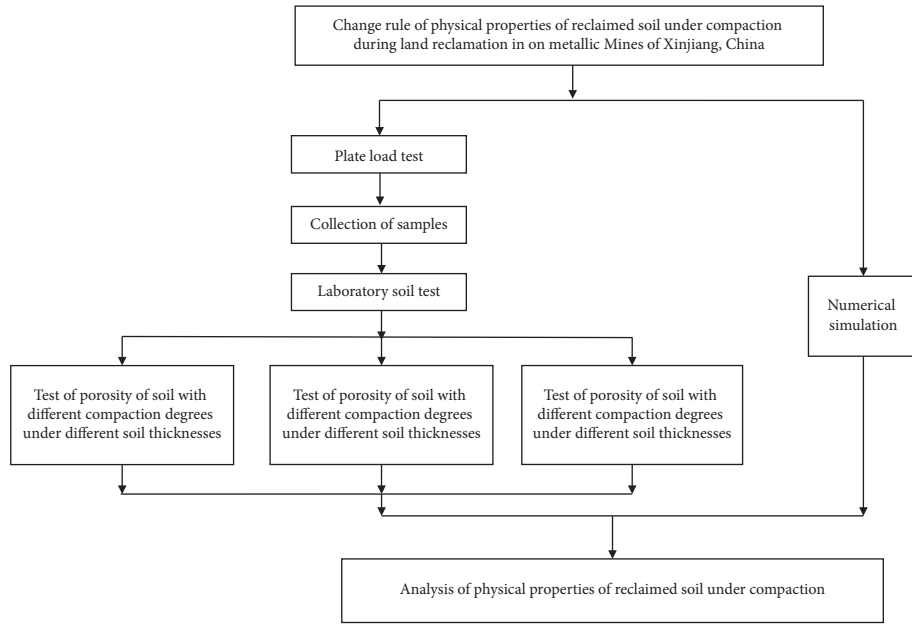
3.3. Calculation Parameters. The calculation parameters in this numerical model were obtained from the results of in situ compaction test. The specific calculation parameters are shown in Table 5.

FIGURE 8: Technology roadmap.

TABLE 1: Results of the compaction experiment.

Thickness of topsoil (cm)	Times of compaction	Depth of sampling (cm)	Average of natural density, ρ (g/cm^3)	Average of water content in mass, ω (%)	Average of porosity (%)
	0	10	1.290	11.76	57.71
	1	10	1.425	11.41	53.15
		30	1.455	12.60	52.68
70	3	10	1.441	10.58	52.23
		30	1.457	12.29	52.47
	5	10	1.447	9.70	51.70
		30	1.460	14.12	53.09
	1	10	1.470	14.23	52.87
		30	1.455	11.23	52.07
50	3	10	1.486	12.93	51.81
		30	1.483	11.67	51.34
	5	10	1.490	11.17	50.92
		30	1.539	15.01	50.97
	1	10	1.512	11.72	50.42
30	3	10	1.552	13.36	49.83
	5	10	1.556	12.71	49.42

Only the average value of each experiment is listed. The water content is expressed in mass. The calculation method is that the mass of water in the soil is divided by the mass of dry soil. The calculation formula of the porosity is $n = 1 - \rho/2.73/(1 + \omega)$.

TABLE 2: Particle size composition of reclaimed soil for numerical calculation model.

Particle size (mm)	0.1–0.25	0.25–0.5	0.5–1	1–2	2–5	5–10
Percentage content (%)	39.58	24.12	18.13	5.73	3.41	9.03

TABLE 3: Dimension table of numerical calculation model.

Model: length × width (cm)	Measure the setting depth of a circle (cm)
159.6 × 10	10
159.6 × 30	10, 30
159.6 × 70	10, 30

The length of the model is equal to the diameter of the cylindrical test barrels (Figure 3).

compaction. With the increase of compaction times, the maximum subsidence of reclaimed soil was gradually increased and the minimum porosity was gradually reduced. Figures 9 and 12 show that, after a compaction, the maximum subsidence of reclaimed soil was 3.2262 cm and the minimum porosity was 0.501. Figures 13–14 show the relationship between the porosity of soil samples and the number of times of compaction, such as 5 times compaction (Figure 14). The porosity of soil sample decreased with the

TABLE 4: Compaction numerical simulation parameters.

Soil thickness (cm)	Compaction times	Measuring the depth of the circle (cm)	Initial porosity	Natural initial density of reclaimed soil (g/cm^3)
30	1, 3, 5	10	0.5771	1.29
50	1, 3, 5	10, 30	0.5771	1.29
70	1, 3, 5	10, 30	0.5771	1.29

TABLE 5: Physical parameters of compaction test numerical simulation.

Simulated porosity	Equivalent modulus (kPa)	Ratio of normal stiffness to tangential stiffness	Friction coefficient between particles	Pressure (kPa)	Damping ratio
0.2842	1.0×10^4	1	1.3	33.7	0.7
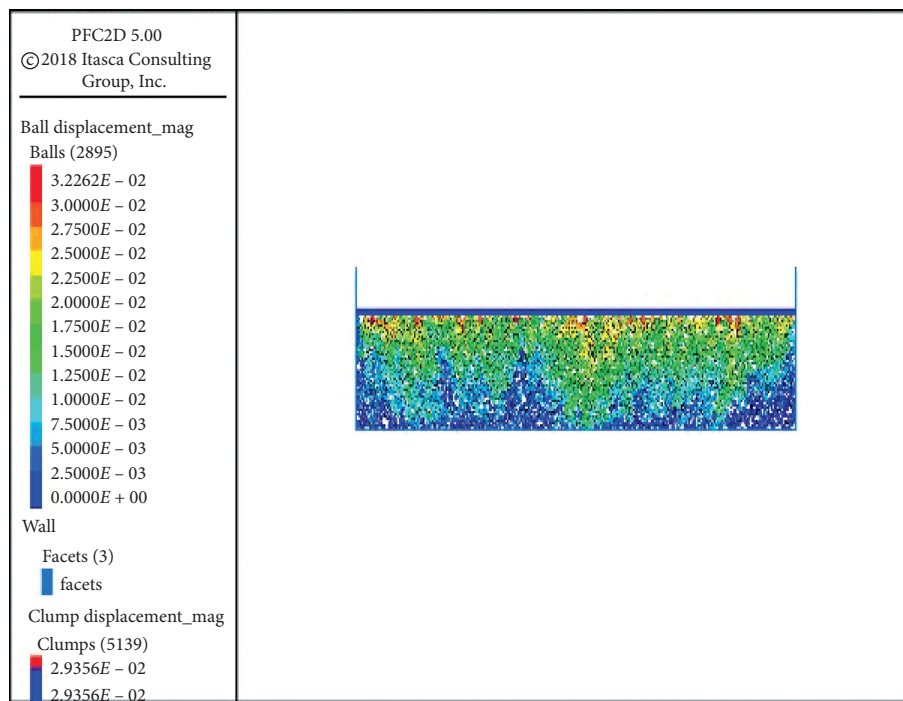
FIGURE 9: Discrete element particle migration map of 30 cm thick reclaimed soil with one compaction.

increase of the number of compactions. At the beginning of compaction, the change amplitude was obvious. After 5 times compaction, it stabilized. In our analysis, the main factors affecting soil porosity are the contact area of the soil particles and the arrangement of the particles. During the compaction process, changes in the soil structure lead to more compacted soil particles, which reduces the soil porosity. After the end of compaction, the soil structure rebounds after unloading, and the structure is basically stable, so the soil porosity also tends to be stable. The porosity obtained by the field compaction test was slightly larger than the minimum value of the numerical simulation, because the soil would rebound slightly during the sampling process.

3.4.2. Numerical Simulation Results of Covered 50 cm Soil Thickness under Compaction. The numerical simulation results of the soil thickness of 50 cm are shown in Figures 15–20 and summarized in Table 7. It should be noted that the initial porosity at the depth of 30 cm was not 0.577, which was due to the redistribution of particles in the initial stage and the filling of small particles into the pores of large particles at the initial stage that cause reduction in the pore rate. Table 7 shows that the law of subsidence of reclaimed soil after compaction was the same as that of covering soil thickness of 30 cm, and the variation of minimum porosity was also reduced with the increase of compaction times. The porosity at the depth of 10 cm was finally lower than that of 30 cm after compaction, indicating that the surface compaction effect of the reclaimed soil was better. Figures 18–20 show that the porosity at the depth of 30 cm was generally less than 10 cm at the first time of compaction. This showed that the compaction effect at the depth of 30 cm was obvious
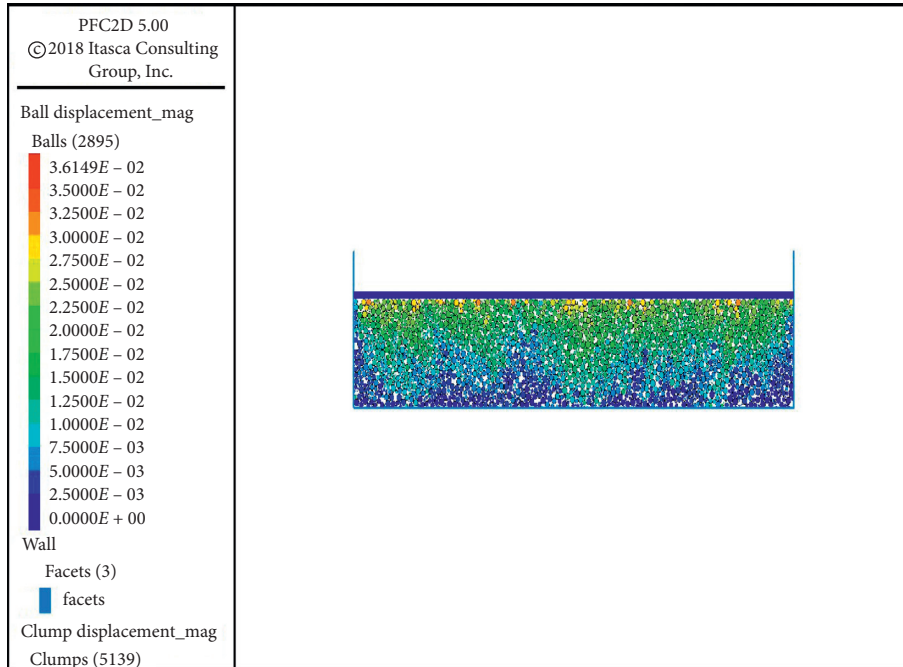
FIGURE 10: Discrete element particle migration map of 30 cm thick reclaimed soil with three compactions.
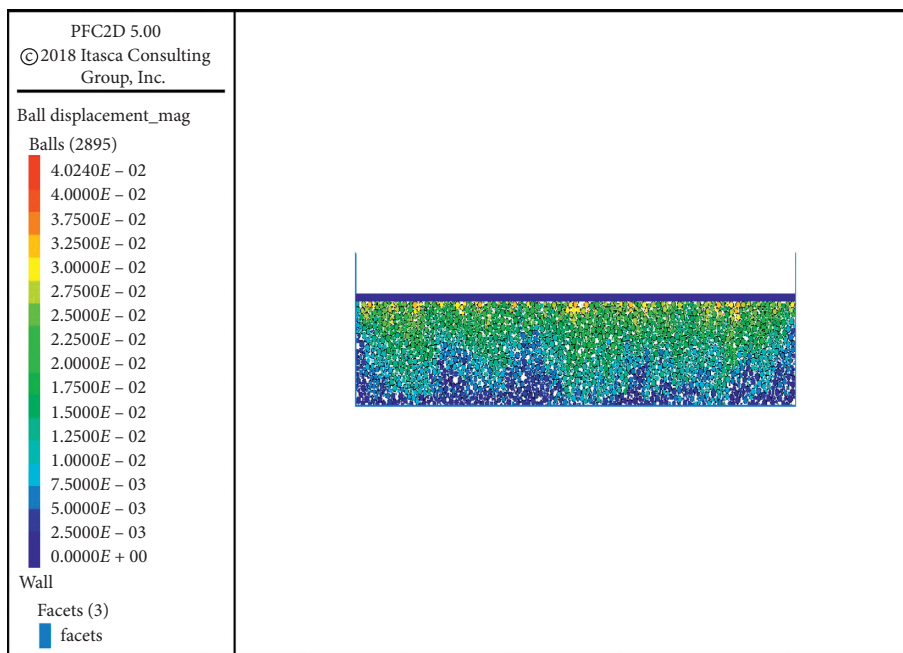

FIGURE 11: Discrete element particle migration map of 30 cm thick reclaimed soil with five compactions.

because of the up-down compression at the beginning of the compaction. With the increase of compaction times, the porosity at the depth of 10 cm was less than 30 cm, which was consistent with the results of the in situ compaction test. After analysis, Under the same conditions, the porosity of the soil decreases with depth. During the compaction process, the surface soil absorbs little compaction energy, the soil structure undergoes greater deformation, and the structure becomes more compact.

Therefore, the soil in the shallow part has better compaction effect than the soil in the deep part.

3.4.3. Numerical Simulation Results of Covered 70 cm Soil Thickness under Compaction.

The numerical simulation results of the soil thickness of 70 cm are shown in Figures 21–26 and summarized in Table 8, which shows that the law of subsidence of reclaimed soil after compaction was
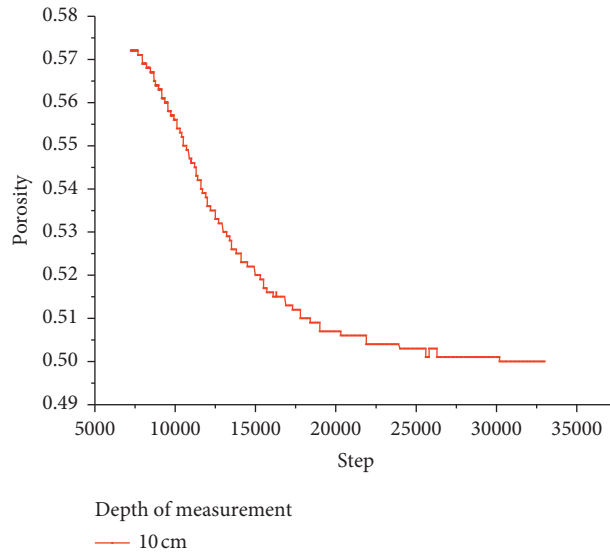
Figure 12: Curve of porosity change of 30 cm thick reclaimed soil with one compaction.
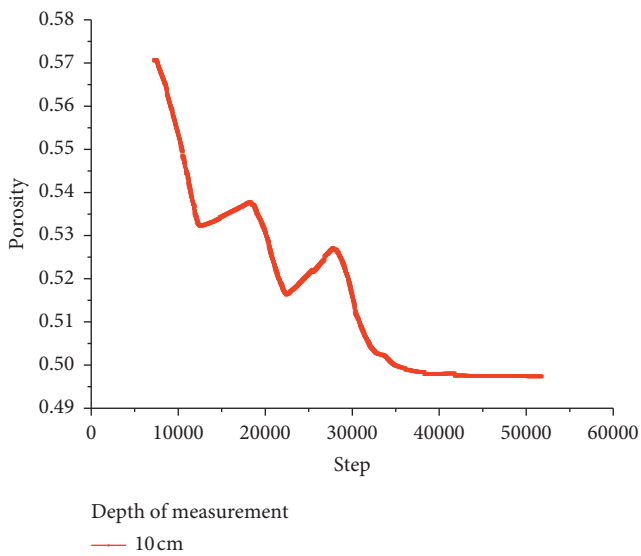

Figure 13: Curve of porosity change of 30 cm thick reclaimed soil with three compactions.
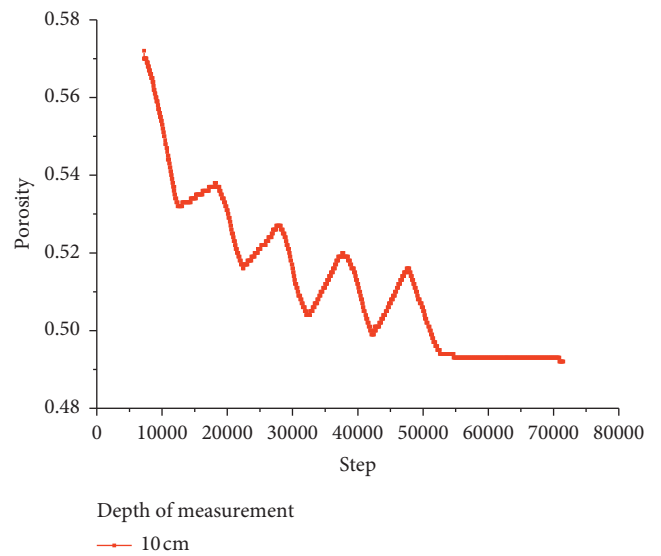

Figure 14: Curve of porosity change of 30 cm thick reclaimed soil with five compactions.

the same as that of covering soils of 30 cm and 50 cm, and the variation of minimum porosity was also reduced with the increase of compaction times. The minimum porosity at 10 cm depth was lower than 30 cm depth after compaction indicating that the compaction effect of the surface reclaimed soil was obvious. The numerical simulation porosity was also smaller than the in situ test result, and the difference reached the maximum; this was because that the soil was thickest and the springback of the soil was the largest. Figures 25 and 26 show that the porosity at the depth of 10 cm decreased and rebounded the most in each compaction process, stating that the compaction effect of the surface of the reclaimed soil was better under compaction. After analysis, the total thickness of the reclaimed soil is one of the main factors affecting the physical properties of the soil under compaction. Under the same conditions, the reclaimed soil with larger overall thickness is weaker in deformation due to compaction energy than the smaller thickness, so the compaction of different thickness of reclaimed soil at the same depth is more different, and the surface compaction of shallower overburden stronger.

TABLE 6: Numerical simulation results for soil thickness of 30 cm.

Compaction times	Maximum subsidence displacement of soil particles after compaction (cm)	Minimum porosity in 10 cm depth of numerical simulation	Porosity obtained by sampling depth of 10 cm in field compaction test	Difference
1	3.2262	0.501	0.5042	0.0032
3	3.6149	0.498	0.4983	0.0003
5	4.0240	0.494	0.4942	0.0002
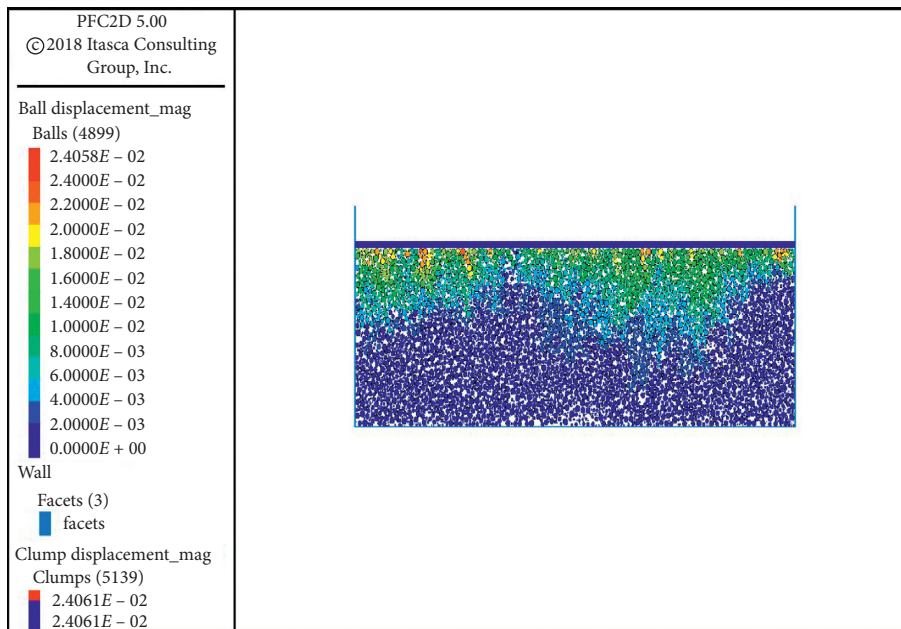
FIGURE 15: Discrete element particle migration map of 50 cm thick reclaimed soil with one compaction.
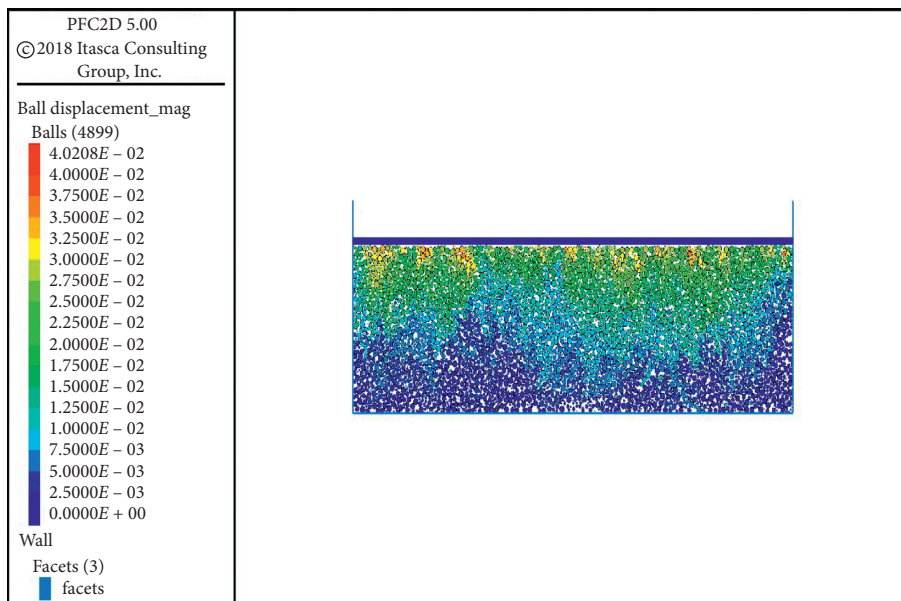
FIGURE 16: Discrete element particle migration map of 50 cm thick reclaimed soil with three compactions.
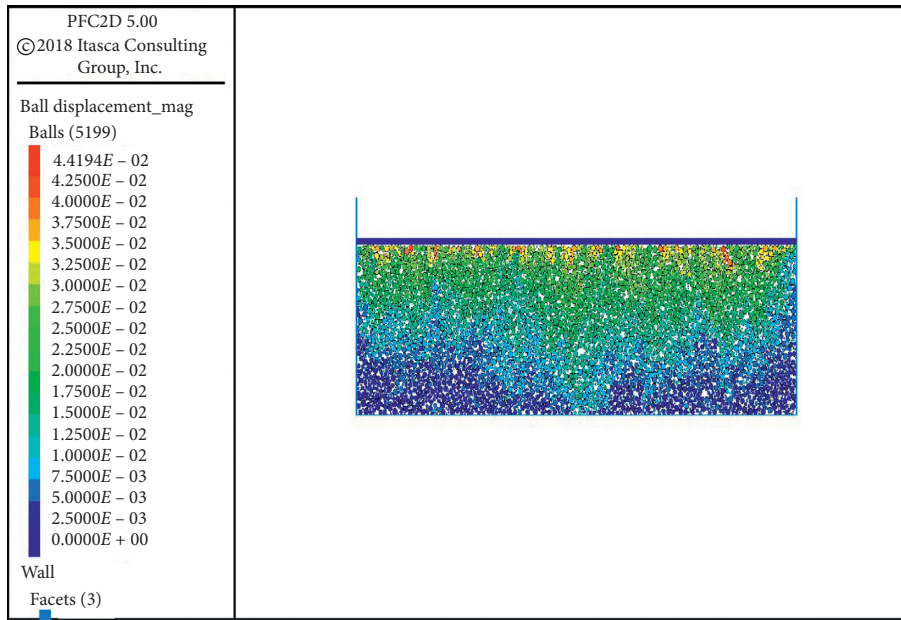
FIGURE 17: Discrete element particle migration map of 50 cm thick reclaimed soil with five compactions.
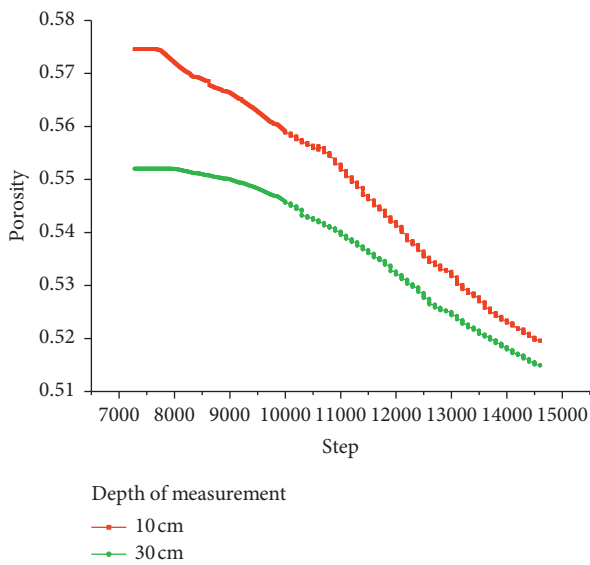

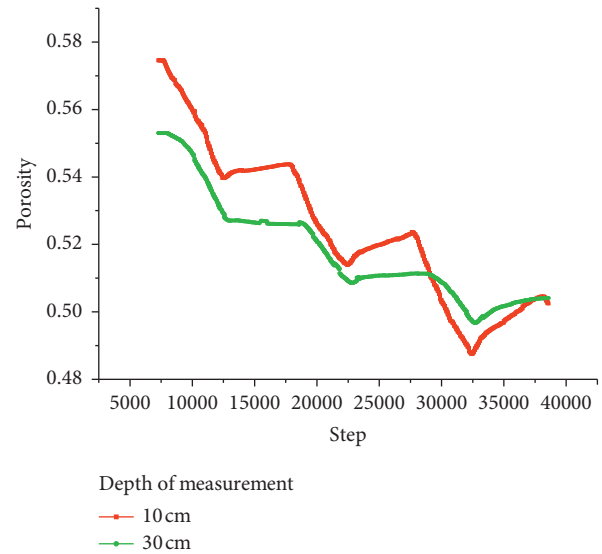FIGURE 18: Curve of porosity change of 50 cm thick reclaimed soil with one compaction.

FIGURE 19: Curve of porosity change of 50 cm thick reclaimed soil with three compactions.

3.5. Comparison of Numerical Simulation and Physical Simulation Results.

The data of numerical simulation results and field physical simulation results were sorted out as shown in Figures 27 and 28. Figures 27 and 28 show that the numerical simulation results are highly consistent with the field physical simulation results. As shown in Figure 27, the thicker the surface reclaimed is, the greater the porosity after compaction will be, which indicates that the overlying soil thickness is negatively correlated with the compaction effect during compaction. Figure 28 shows that the effect of compacting three times is the most obvious, and the effect of single compaction is weakened with the increase of the number of compaction. The porosity at the depth of 30 cm is less than that at the depth of 10 cm at the first compaction, indicating that at the initial stage the compaction effect of the middle part of the reclaimed soil is obvious by the upper and lower extrusion. With the increase of the number of compaction, the porosity at the depth of 10 cm is less than 30 cm, and the compaction effect on the surface of the soil is obvious.
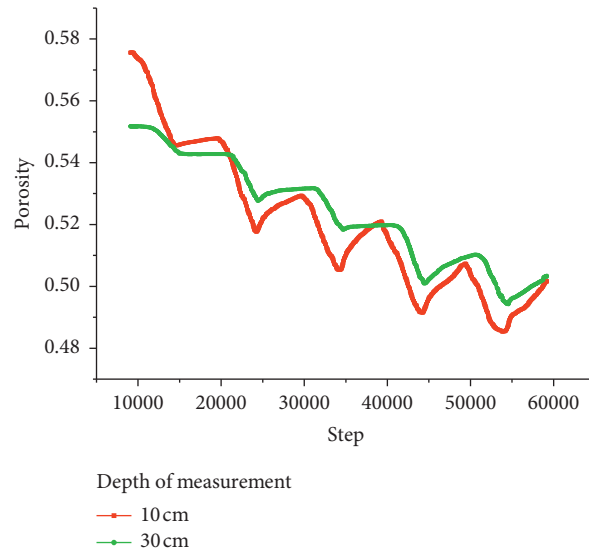
FIGURE 20: Curve of porosity change of 50 cm thick reclaimed soil with five compactions.

TABLE 7: Numerical simulation results for soil thickness of 50 cm.

| Compaction times	Maximum subsidence displacement of soil particles after compaction (cm)	Minimum porosity of numerical simulation		Porosity obtained by field compaction test		Difference	
		Depth 10 cm	Depth 30 cm	Depth 10 cm	Depth 30 cm	Depth 10 cm	Depth 30 cm
1	2.4058	0.52	0.5197	0.5287	0.5207	0.0087	0.001
3	4.0208	0.49	0.5011	0.5187	0.5134	0.0287	0.0123
5	4.4194	0.484	0.50	0.5092	0.5097	0.0252	0.0097
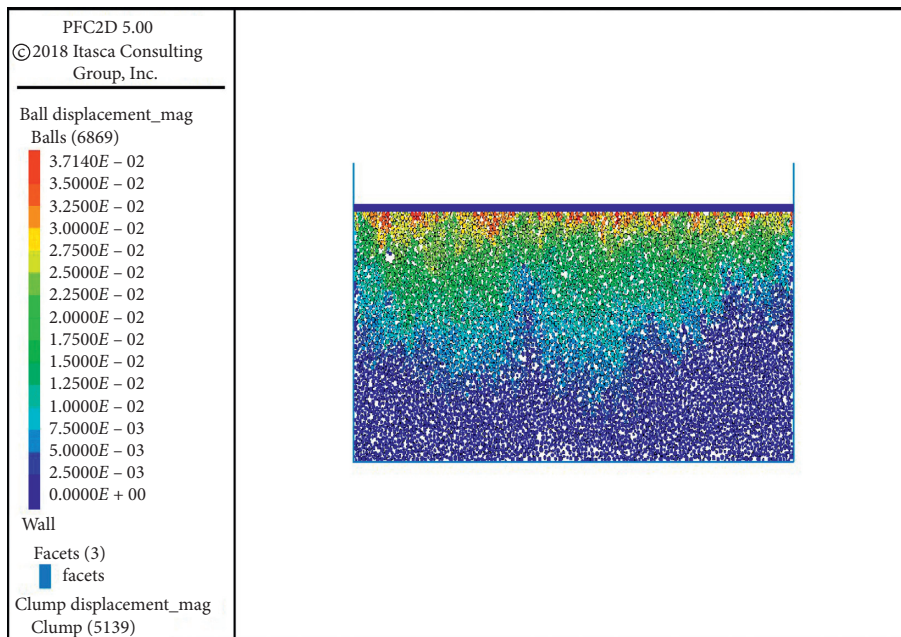
FIGURE 21: Discrete element particle migration map of 70 cm thick reclaimed soil with one compaction.
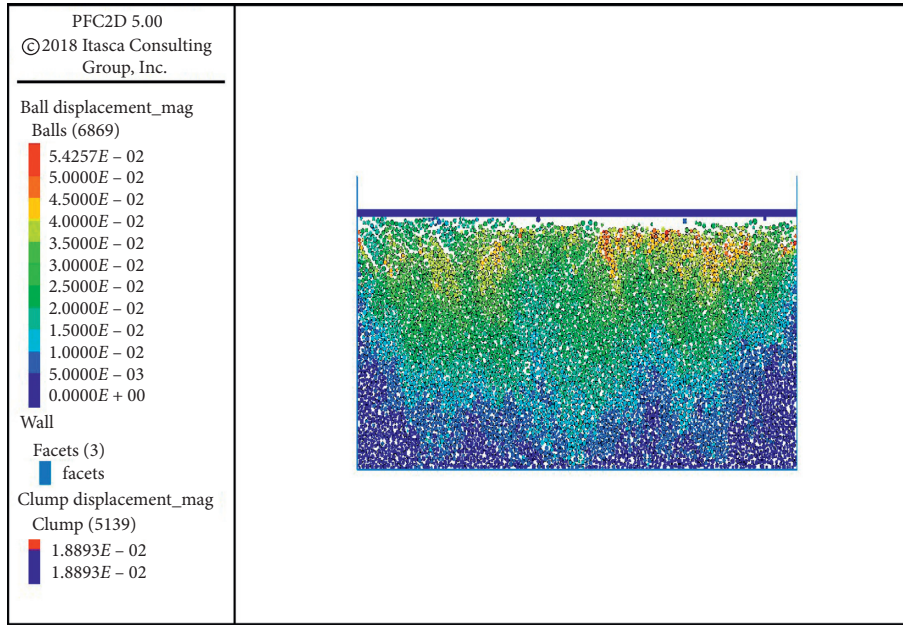
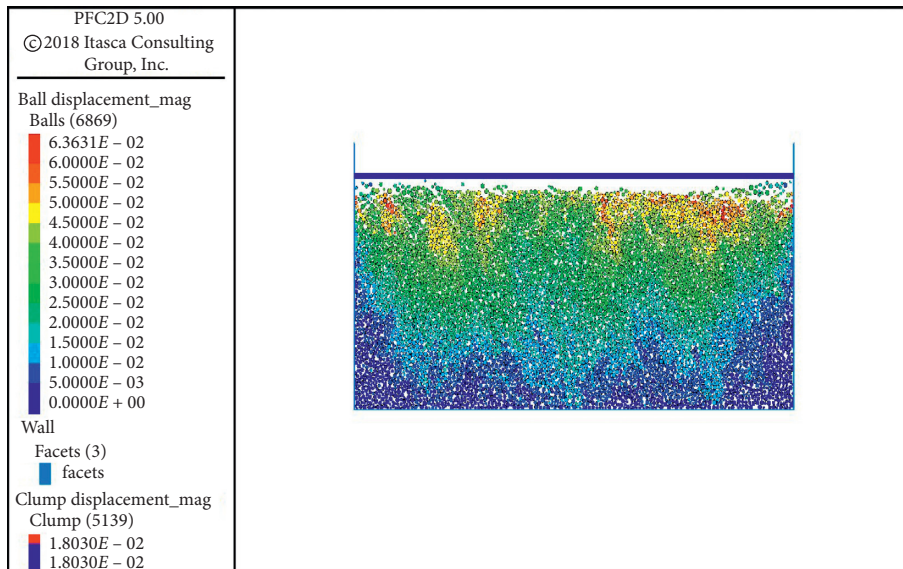Figure 22: Discrete element particle migration map of 70 cm thick reclaimed soil with three compactions.

Figure 23: Discrete element particle migration map of 70 cm thick reclaimed soil with five compactions.
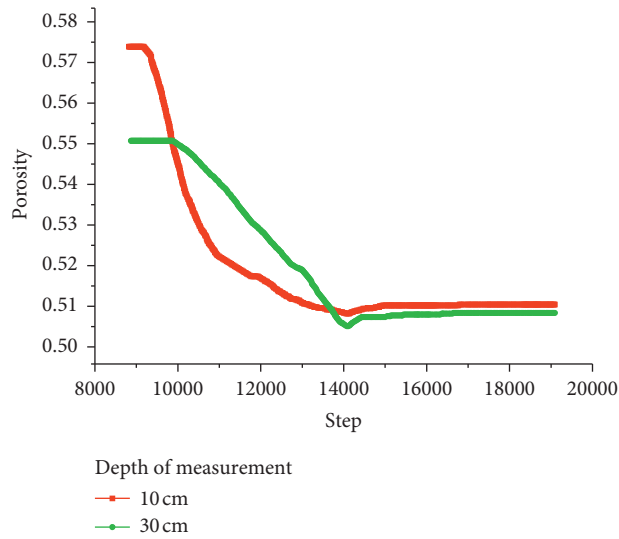
Depth of measurement
— 10 cm
— 30 cm

FIGURE 24: Curve of porosity change of 70 cm thick reclaimed soil with one compaction.
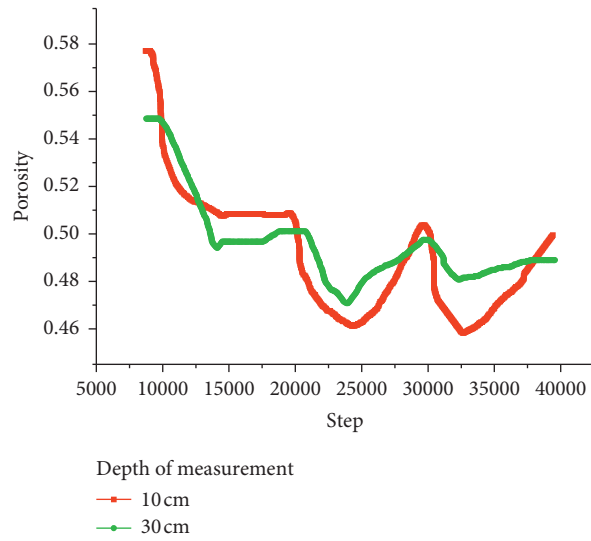

Depth of measurement
— 10 cm
— 30 cm

FIGURE 25: Curve of porosity change of 70 cm thick reclaimed soil with three compactions.

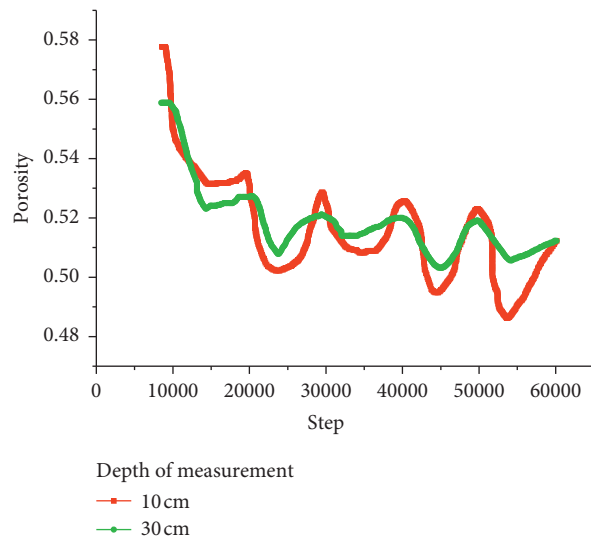
Depth of measurement
— 10 cm
— 30 cm

FIGURE 26: Curve of porosity change of 70 cm thick reclaimed soil with five compactions.

TABLE 8: Numerical simulation results for soil thickness 70 cm.

Compaction times	Maximum subsidence displacement of soil particles after compaction (cm)	Minimum porosity of numerical simulation		Porosity obtained by field compaction test		Difference	
		Depth 10 cm	Depth 30 cm	Depth 10 cm	Depth 30 cm	Depth 10 cm	Depth 30 cm
1	3.7147	0.528	0.525	0.5396	0.5268	0.0046	0.0018
3	5.4257	0.502	0.514	0.5223	0.5247	0.0123	0.0107
5	6.3631	0.488	0.508	0.5170	0.5309	0.015	0.0229
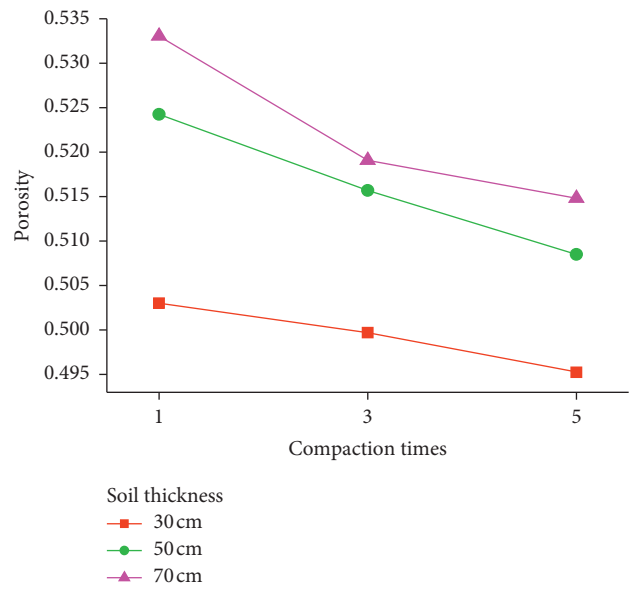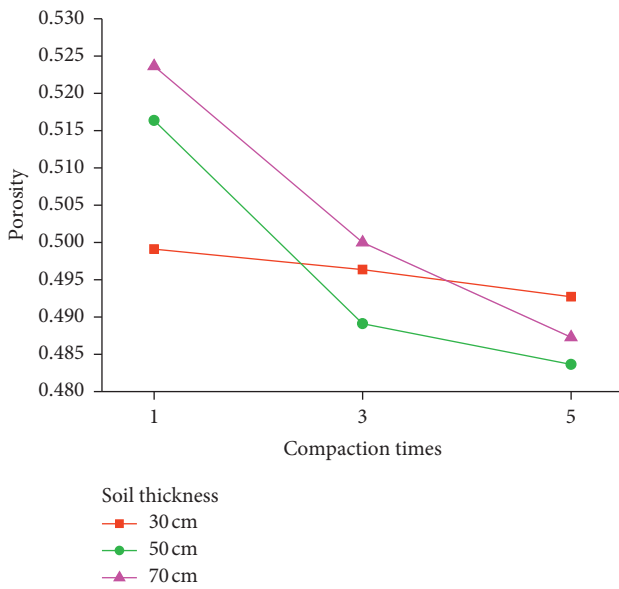
FIGURE 27: Curves of porosity of different thicknesses of soil with different compaction times: the results of (a) numerical simulation and (b) physical simulation.
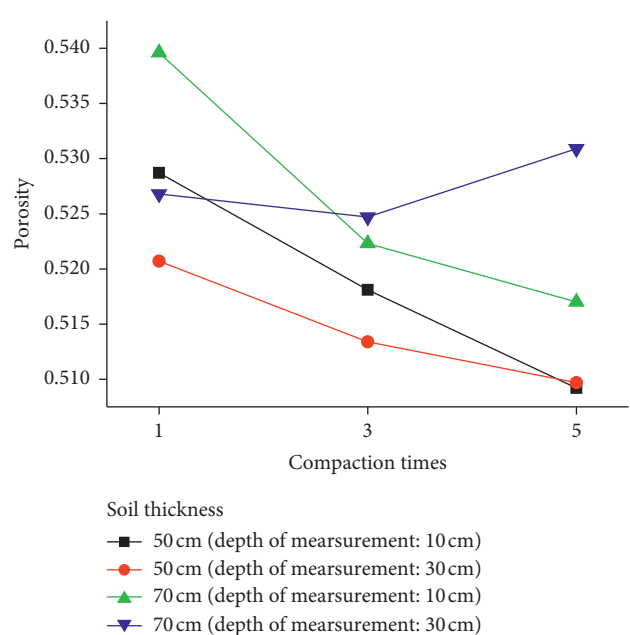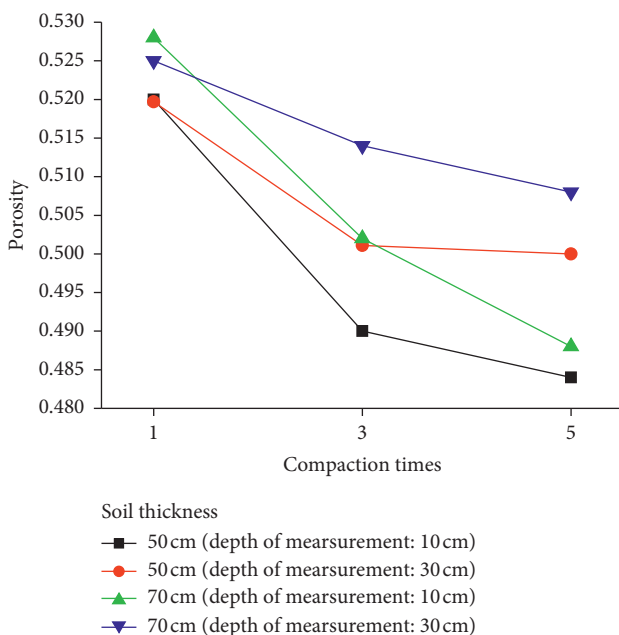
FIGURE 28: Curves of porosity of different thicknesses of soil and different depths with different compaction times: the results of (a) numerical simulation and (b) physical simulation.

4. Conclusions

Studying the soil compaction effect of reclaimed soil is significant for ecological restoration of mining areas. In this paper, the compaction of reclaimed soils from non-metallic mines in Xinjiang is studied. Based on the field physical simulation experiment, this paper mainly used the numerical simulation method to study the change process of porosity of reclaimed soils with different thickness under different compaction. Through the analysis of physical and numerical simulation results, it was concluded that the numerical simulation results of reclaimed soil compaction were consistent with the experimental results of physical simulation. The final porosity of reclaimed soil obtained by numerical simulation was smaller than physical simulation test result because of the springback of the reclaimed soil during the sampling process. The numerical simulation results were more realistic because they were not affected by the sampling process and the limitation of experimental methods. The effect of reclamation machinery on three times compaction of soil was significantly different from that of non-compaction. With the increase of compaction times, the effect of single compaction decreased. The thicker the overlying soil layer was, the less obvious the compaction effect was. The effect of reclamation machinery on the compaction of different depths was different. The compaction effect of reclamation machinery on the shallow part of reclaimed soil (depth 10 cm) was the greatest. The porosity at the initial 30 cm depth was less than 10 cm depth. With the increase of compaction times, the porosity at the depth of 10 cm was less than that at the depth of 30 cm, which indicated that the effect of surface compaction is obvious.

Data Availability

The data used to support the findings of this study are included within the article. All data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Z.Z. conceived the main idea of the paper and designed the test scheme; K.W., F.S., G.T., and X.L. performed the test scheme; K.W. and G.T. analyzed the data; Z.Z. wrote the paper; W.S. did a lot work to modify figures and proofread the revised version. D.T. and Q.L. reviewed and seriously revised the article after it was withdrawn.

Acknowledgments

Supplementary Materials

The supplementary material is a graphical abstract to illustrate the main content of this article. (*Supplementary Materials*)

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